FINAL TECHNICAL REPORT

to the

Air Force Office of Scientific Research

on research in

FLOW CONTROL

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(URI in Flow Control)

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1. EXECUTIVE SUMMARY

1.1 Motivation and Objectives

The ability to control fluid flows offers many new opportunities. For example, on flight vehicles it may be possible do the following:

- control the airflow over a wing to prevent vortex breakdown at high angle of attack in a supermaneuver;
- stabilize turbulent boundary layer flow to keep it laminar and thereby reduce drag;
- suppress separation in transient flows to improve propulsion performance;
- enhance mixing in jet ejectors to obtain compact thrust augmentors.

Thus, there is considerable incentive to develop our national capability in *flow control*, and this program was designed to contribute to this development.

The general objective of this program was to make significant advances in the engineering science and technology of flow control. The research team consisted of faculty and PhD students in the closely-knit Departments of Aeronautics/Astronautics and Mechanical Engineering, who joined together to apply their expertise in fluid mechanics, aeronautics, and automatic control in a coordinated effort to advance the field of flow control.

1.2 Program Structure

The program was organized into three primary tasks:

1. control of jet flows;
2. control of unsteady turbulent boundary layers;
3. control of vortical flow over delta wings

Task 1 was an outgrowth of our discovery of the phenomena of *bifurcating and blooming jets*, in which the proper combination of streamwise and helical excitations cause dramatic increases in the entrainment and spreading rates, and dealt with open and closed-loop control of round turbulent jets. Task 2 was an outgrowth of our work on unsteady turbulent boundary layer and active separation control, and focused on methods for actuating boundary layer control. It also included the development of a new holographic method for measurement of vorticity. Task 3 was a study of the use of tangential leading edge blowing on a delta wing to control the vortical flow above the wing for purposes of aerodynamic control. The projects were managed separately, but there was significant exchange of information between the programs and a general sharing of the knowledge developed in each program.

1.3 Summary of Important Results

Work under each task has been described in detail in a comprehensive set of reports and journal articles arising from the work. Here we summarize the key results with pointers to the appropriate publications containing the details. The program served to bring together faculty in fluid dynamics and automatic controls, who now continue to interact in new research under other support. In addition, it created a cadre of fluid mechanics faculty familiar with the problems and opportunities in the application of feedback control to complex fluid flows, and served to initiate other work in this general area.

Task 1 - Control of jet flows:

This work showed that bifurcation and blooming can be made to occur in high Reynolds number jets at moderate subsonic Mach numbers with rather moderate levels of properly designed acoustic forcing [1]. Substantial increases in entrainment were measured when control was applied in a configuration equivalent to a very short thrust augmentor or jet ejector [2,3,5]. When tangential blowing (suggested by Task 3) was explored as a method for reducing the strength of acoustic excitations required for control, it was found that moderate blowing would cause a complete redirection of the jet into a radial wall jet (a Coanda jet). Work in this flow is continuing under other support.

The systems described above all involved open-loop scheduled control. In the study of closed loop control, it was shown that standard feedback control theory could be used to design a control system for stabilizing the jet flow emerging from a conical diffuser [4,6].

Task 2 - Control of unsteady turbulent boundary layers:

Studies in air flows examined the control of boundary layer separation using actuated delta vortex generators [11] and vortex actuator jets [8]. Detailed hotwire measurements revealed the temporal features of the flow after a rapid vortex actuation and deactuation. In a companion study, the characteristics of the vortical flow downstream of vortex generator jets was mapped for a range of jet parameters. Both techniques were shown to be effective at controlling boundary layer separation.

Control of the flow downstream of an oscillating spoiler was studied in air as an example of simple unsteady separating flow [9,10]. Detailed temporal features of the flow were examined, and simple, wall-based techniques for the detection of the vortex strength and position were developed. Passive control techniques failed in this flow, but active blowing through slots was an effective technique.

Studies in water flow examined the use of steady delta generators to control separation in an unsteady turbulent boundary layer [12]. Detailed LDA measurements showed that the generators significantly reduce the adjustment time of a boundary layer responding to a step change in free-stream pressure gradient.

As an adjunct to the experimental studies in water, a novel method was developed for direct measurement of the vorticity in water flows, based on the deformation rate of a tiny local grid written into the fluid by holography [13-15]. This new technology will be especially important a pending AFOSR program on microflows.

Task 3 - Control of vortical flow over delta wings:

It was shown that the vortical flow over a delta wing with blunt leading edge can be controlled using tangential leading edge blowing [16-21]. This control allows rapid manipulation of the vortical flow field, and can achieve stable vortical flow without large-scale separation at very high angles of attack. It can be used in place of mechanical control surfaces for control of the aircraft roll and pitch moments [23-26].

Non-linear CFD methods and simplfied potential flow calculations were used to estimate the unsteady flow field in the presence of unsteady blowing. This model was used to verify the feasibility of aircraft lateral control using blowing [23]. Detailed measurements of unsteady surface pressures and vortex positions in response to changes in the blowing rate over a model delta wing were used to determine the parameters used in the design of an active control system that was subsequently demonstrated in a simple experiment (not yet published). A new approach to aircraft design and control was developed [27], and is now ready to be used with this control technology.

As part of this program, new pulsed laser sheet diagnostic methods for visualizing unsteady vortical flows, quantifying the vortex location and scale, and for displaying complex three-dimensional datafields were developed [22,26]. These are expected to be of considerable use in future research on complex flows.

1.4 Impact of Funding Disruptions

The project was initially funded at approximately the proposed level, which was minimal for conduct of the proposed program. Congressional action subsequently placed a cap on URI funding in any state, with the result that funding for this project (as for other URIs in California) was reduced by approximately 40% for the second year. With special help form the university and participating departments, and by reducing the level of equipment purchase, we were able to sustain the momentum built up in the first year, and consequently we did not reduce the work scope from that originally proposed. In the third year the situation was better, because the AFOSR chose to distribute the reduction evenly across the URI program. The program was terminated at the end of year three, but a no-cost extension period and Stanford funding supplements enabled us to maintain an active team for part of the fourth year. The net effect was that we were able to complete the propose program of research essentially as originally planned.

Nevertheless, the impact on the faculty who experienced this very disruptive situation should be noted. As a result of the severe problems that surrounded these disruptions, several of the participating faculty now have reduced enthusiasm for cooperation in large, interdisciplinary research programs, especially where funding decisions are likely to be influenced by politics, and this is indeed unfortunate for the nation.

2. PUBLICATIONS FROM THIS PROJECT

Work under this project resulted in many publications, provided previously to the AFOSR by the researchers in the three tasks. These publications are summarized below.

Task 1 - Control of jet flows:

1. PAREKH, D., LEONARD, A. & REYNOLDS, W.C. Bifurcating jets at high Reynolds numbers. *Rept. TF-35*, Dept. of Mech. Engrg., Stanford U., 1988
2. JUVET, P.J.-D. & REYNOLDS, W.C. Entrainment control in an acoustically controlled shrouded jet. *AIAA-89-0969*, Symposium on Flow Control, Tempe, AZ 1989.
3. KOCH, C.R., MUNGAL, M.G., REYNOLDS, W.C. & POWELL, J.D. Helical modes in an acoustically excited round air jet. *Phys. Fluids A*, 1429, 1989.
4. KOCH, C.R., POWELL, J.D. & REYNOLDS, W.C. An experimental investigation of closed loop control of a round jet/diffuser. *AIAA 90-0241*, Reno, Nevada 1990
5. JUVET, P.J.-D. & REYNOLDS, W.C. Control of organized structures in round jets at high Reynolds numbers. *NATO Workshop on the Global geometry of Turbulence*, Rota, Spain, July 1990.
6. KOCH, C.R. Closed loop control of a round jet/diffuser in transitory stall. *Dissertation Report*, Guidance and Control Laboratory, Dept. Aeronautics/Astronautics, Stanford U., October 1990.

Task 2 - Control of unsteady turbulent boundary layers:

7. NELSON, C.F., KOGA, D.J. & EATON, J.K. Control of the unsteady, separated flow behind an oscillating two-dimensional flap. *AIAA 2nd Shear Flow Control Conf.*, Tempe, AZ 1989.
8. JOHNSTON, J.P. & NISHI, M. Vortex generator jets - a means for flow separation control. *J. AIAA*, **28**, June 1990, 989-994.
9. NELSON, C.F., KOGA, D.J. & EATON, J.K. Unsteady separated flow behind an oscillating two-dimensional spoiler. *AIAA J.*, **28**, 845-852, 1990.
10. NELSON, C.F., EATON, J.K. & KOGA, D.J. Measurement and control of the unsteady separated flow downstream of an oscillating spoiler. *Rept. MD-59*, Dept. of Mech. Engrg., Stanford U., Dec. 1990.
11. LITTELL, H.S. & EATON, J.K. The unsteady flowfield behind a vortex generator rapidly pitched to angle of attack. *AIAA J.*, to appear.

12. HUMPHREYS, W.W & REYNOLDS, W.C. An experimental study of the effect of streamwise vortices on unsteady turbulent boundary layer separation. *Rept. TF-42*, Dept. of Mech. Engrg., Stanford U., December 1988.

13. AGUI, J.C. & HESSELINIK, L. Holograms in motion. I. Effect of fluid motion on volume holograms. *J. Optical Soc. Amer. A*, **5**, 1287, August 1988.

14. AGUI, J.C. & HESSELINIK, L. Holograms in motion. II. Diffracting Capabilities of Strained Holograms. *J. Optical Soc. Amer. A*, **5**, 1287, August 1988.

15. AGUI, J.C. & HESSELINK, L. Holographic measurement of velocity gradients in fluid flows sensitized with photochromic dyes. *Proc. 10th Australasian Fluid Mechanics Conference*, Melbourne, Australia, December 1989.

Task 3 - Control of vortical flow over delta wings:

16. WOOD, N.J., ROBERTS, L. & LEE, K.T. The control of vortical flow on a delta wing at high angles of attack. *AIAA 87-2278*, Applied Aerospace Meeting , Monterey, CA., August 1987.

17. YEH, D., TAVELLA, D. & ROBERTS, L. Numerical study of delta wing leading edge blowing. *Rept. JIAA TR-86*, Dept. Aeronautics/Astronautics, Stanford U., Stanford, CA, July 1988.

18. WOOD, N.J. & ROBERTS, L. Control of vortical lift on delta wings. *J. Aircraft*, **25**, 236-243, March 1988.

19. YEH, D., TAVELLA, D., ROBERTS, L. & FUJII, K. Navier-Stokes computation of the flow field over delta wings with spanwise leading edge blowing. *AIAA 88-2558*, 6th Applied Aerodynamics Conference, Williamsburg, VA, June 1988.

20. WOOD, N.J., ROBERTS, L. & CELIK, Z. The control of asymmetric vortical flows over delta wings at high angles of attack. *AIAA 89-3347*, August 1989.

21. ROBERTS, L. & WOOD, N.J. Control of vortex aerodynamics at high angles of attack. 65th AGARD Fluid Dynamics Symposium, Madrid, Spain, October 1989.

22. YODA, M. & HESSELINK, L. Three-dimensional measurement, display, and interpretation of fluid flow datasets. *SPIE Proc.*, **1083**, 14-19, January 1989.

23. MITTELMAN, Z. & KROO, I. Unsteady aerodynamics and control of delta wings with tangential leading-edge blowing. *AIAA 89-3374* Flight Mechanics Conference, August 1989

24. CELIK, Z., ROBERTS, L. & Wood, N.J. An investigation of asymmetric vortical flows over delta wings with tangential leading-edge blowing at high angles of attack. *AIAA 90-103*, 28th Aerospace Sciences Meeting, Reno, Nevada January 1990.

25. LEE, K.T. & ROBERTS, L. Controlled vortical flow on delta wings through unsteady leading edge blowing. *Rept. JIAA TR-97*, Dept. Aeronautics/Astronautics, Stanford U., January 1990.

26. YODA, M. & HESSELINK, L. A three-dimensional visualization technique applied to flow around a delta wing. *Expts. in Fluids*, October 1990.

27. MORRIS, S.J. & KROO, I. Aircraft design optimization with dynamic performance constraints. *J. Aircraft* December 1990.

3. STUDENTS TRAINED BY THIS PROJECT

This project formed the primary basis of support for a number of PhD students who have or will soon receive their degrees. They are listed below. The graduates are now involved in research in other universities, national laboratories, and aerospace companies, and one is an Air Force Lt. Col. now serving as Professor at the U.S. Air Force Academy.

Task 1 - Control of jet flows:

D.E. Parekh, PhD ME 1989
C.R. Koch, PhD ME 1990
P.J.-D. Juvet, PhD ME expected 1991

Task 2 - Control of unsteady turbulent boundary layers:

J.C. Agui, PhD Aero/Astro 1988
W.W. Humphreys, PhD ME 1989
C.F. Nelson, PhD ME 1990

Task 3 - Control of vortical flow over delta wings:

G. Wong, PhD Aero/Astro 1988
K.T, Lee, PhD Aero/Astro 1988
D. Yeh, PhD Aero/Astro 1988
Z. Mittelman, PhD Aero/Astro 1989
M. Yoda, PhD Aero/Astro expected 1992

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13. ABSTRACT *(Maximum 200 words)*

This report outlines a coordinated set of research programs on flow control. The work was carried out by a team of experts in fluid mechanics and automatic control. Jets, turbulent boundary layers near separation, and delta wing flows formed the basis for these studies aimed primarily at developing fundamentals needed for active control of flows of technical interest.

14. SUBJECT TERMS
Flow control, turbulent jets, unsteady boundary layers, delta wing flows.

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